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Integrated palaeoecology and archaeology – a powerful approach for understanding pre-Columbian Amazonia

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ABSTRACT

The old paradigm that Amazonia's tropical ecosystems prevented cultural development beyond small-scale shifting agricultural economies, that had little environmental impact, no longer holds true for much of Amazonia. A diversity of archaeological evidence, including *terra preta* soils, raised fields, causeways, large habitation mounds, geometric earthworks, and megalithic monuments, all point to considerable cultural complexity and environmental impacts. However, uncertainty remains over the chronology of these cultures, their diet and economy, and the scale of environmental impact and land use associated with them. Here, we argue that a cross-disciplinary approach, closely coupling palaeoecology and archaeology, can potentially resolve these uncertainties. We show how, with careful site selection (pairing small and large lakes, close proximity to archaeological sites, transects of soil pits) and choice of techniques (e.g., pollen, phytoliths, starch grains, charcoal, stable isotopes), these two disciplines can be successfully integrated to provide a powerful tool for investigating the relationship between pre-Columbian cultures and their environment.

1. Introduction

In the early 1990s, the geographer William Denevan wrote a land-mark article (Denevan, 1992), where he claimed that the traditional paradigm of Amazonia as a virgin wilderness was in reality a "pristine myth", instead arguing for the presence of neotropical pre-Columbian (pre-A.D. 1492) societies that were both more complex, and had considerably greater environmental impacts, than the post-Columbian semi-sedentary tribes practicing shifting agriculture. Since then, Denevan's ideas have gathered increasing support from new archaeological investigations in different parts of Amazonia, which have begun to reveal sizeable, regionally organized, complex societies during the late Holocene that were not merely passively adapted to their environment (Meggers, 1971), but in many cases actively transformed it on a landscape scale, over thousands of square kilometres (Heckenberger and Neves, 2009; McEwan et al., 2001; Denevan, 2001, 2007). For example, renewed excavations on Marajó island (a landmass the size of Switzerland) at the mouth of the Amazon river, carried out by Roosevelt (1991) and Schaan (2004, 2012), have revealed complex societies that built massive settlement mounds and produced great-art-style ceramics throughout the savanna-dominated eastern half of the island. Most of the bluffs lining Amazonia's major rivers contain anthropogenic, black-earth *terra preta* soils associated with intensive agriculture, and in many cases mounded architecture – pointing to the presence of sizeable complex societies (Heckenberger et al., 1999; Neves and Petersen, 2006; Rebellato et al., 2009). In the Upper Xingu river catchment (towards the southern margin of the Brazilian Amazon), Heckenberger and his collaborators have documented the presence of well-designed road networks connecting clusters of late pre-historic plaza villages across ~17,500 km^2 in what they argue are the origins of Amazonian urbanism (Heckenberger et al., 2003, 2008; Schmidt, 2010). Similar regional networks of ring villages have been documented in a study area of about 900 km^2 in Goiás, Central Brazil by Wüst and Barreto (1999). Deforestation for cattle ranching in eastern Acre state, western Amazonia, has exposed hundreds of "geoglyphs" across ~20,000 km^2 – geometrically-patterned anthropogenic earthworks, comprising circles, squares, and/or rectangles, between 90 and 300 m diameter (Pärssinen et al., 2009; Schaan, 2012; Schaan et al., 2007) (Figs. 1B and 2). In Amapá State, NE Brazilian Amazonia,

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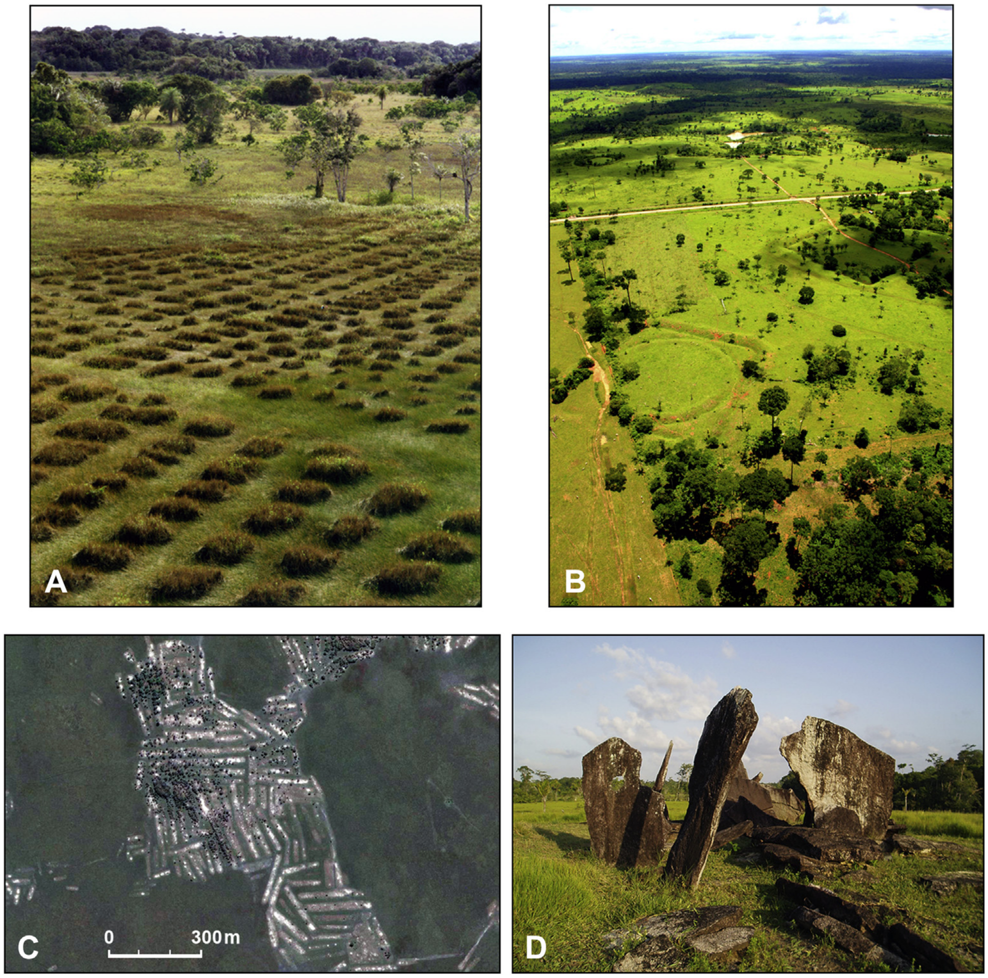

Fig. 1. A: Raised fields from coastal French Guiana (raised-field diameter between 3 and 5 m) (Photo: S. Rostain, 1989). B: Jaco Sa geoglyph, Acre, Brazil (maximum dimension of quadrangle enclosing the circle in the foreground ca. 130 m) (Photo: Sergio Vale/Projeto Geoglifos). C: Raised fields from the region of Santa Ana de Yacuma, Llanos de Mojos, Bolivia (Google Earth). D: Calçoene megalith, northern coast of Amapa state, Brazil (height of tallest granite block approx. 3 m).

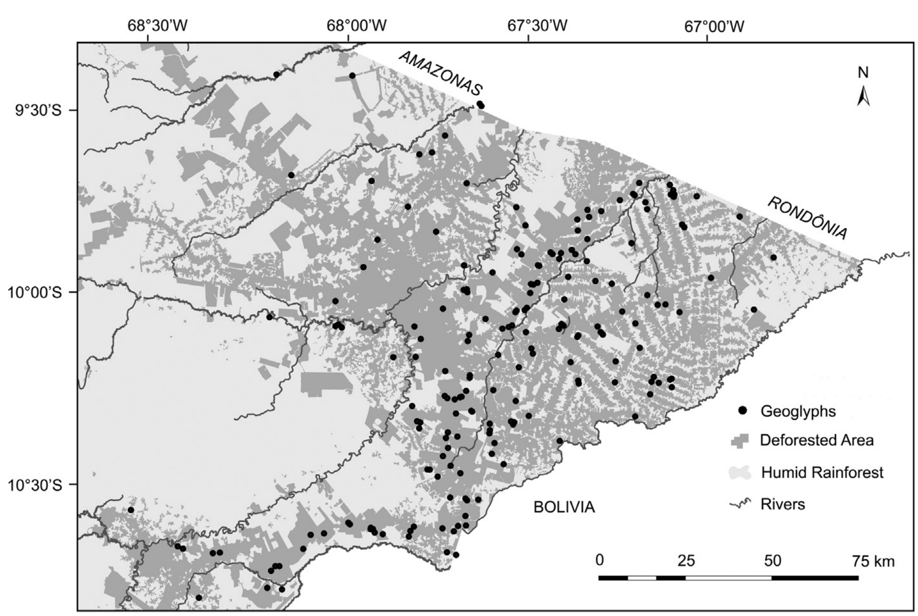

Fig. 2. Map showing the large concentration (>300) of pre-Columbian geometric earthworks ('geoglyphs') that have been discovered in recently deforested areas of eastern Acre state, southwestern Amazonia (with permission from Denise Schaan).

more than 30 sites with megalithic structures, generally consisting of numerous granite blocks arranged in circles, some standing 3 m high and enclosing chambered tombs containing funerary urns, have been discovered along a stretch of ~100 km of coastal rainforest (Cabral and Saldanha, 2008) (Fig. 1D). Similarly, many seasonally-flooded savannas across Amazonia were re-shaped into intensive raised- and drained-field agricultural landscapes – in areas such as the Beni basin in Bolivia (Erickson, 1995, 2006; Lombardo et al., 2011a) (Fig. 1C), the Mompos depression in Colombia (Plazas, 1993), Barinas in Venezuela (Redmond and Spencer, 2007), and the coastal belt of the Guianas (Rostain, 2010) (Fig. 1A), to mention a few. The landscape of the Beni basin in particular (roughly the size of England) was extensively altered, not only by raised fields (covering at least 8000 km^2, Denevan, 1966), but also construction of impressive settlement mounds (Lombardo and Prümers, 2010; Prümers, 2009), extensive road/causeway networks (Erickson, 2006), and, what appear to be, landscape-scale fisheries (Erickson, 2000) (Fig. 3).

However, important questions remain unanswered. In particular, how do these different cultures compare in terms of: i) the geographic scale of environmental disturbance/deforestation (e.g., small-scale forest clearings versus large-scale clear-cutting), ii) their economy and land-use strategies, and iii) the chronology, and underlying drivers (e.g., climatic, political, demographic), of their development and demise? (Note that, for the purposes of this paper, we arbitrarily define: i) small (local) scale as < 1 km^2, ii) large (regional) scale as 1–1000 km^2, and iii) landscape scale as $>$1000 km^2)

Determining the scale of environmental impact by pre-Columbian societies in Amazonia has important implications, not only for archaeology and anthropology, but also tropical ecology and conservation. If pre-Columbian peoples actively altered forest biodiversity by selectively favouring economically important/edible species over others (Balée, 1989; Erickson and Balée, 2006), then the conservation community needs to be aware that these ecosystems may not only be highly resilient to indigenous land-use practices, but the very biodiversity that conservationists seek to

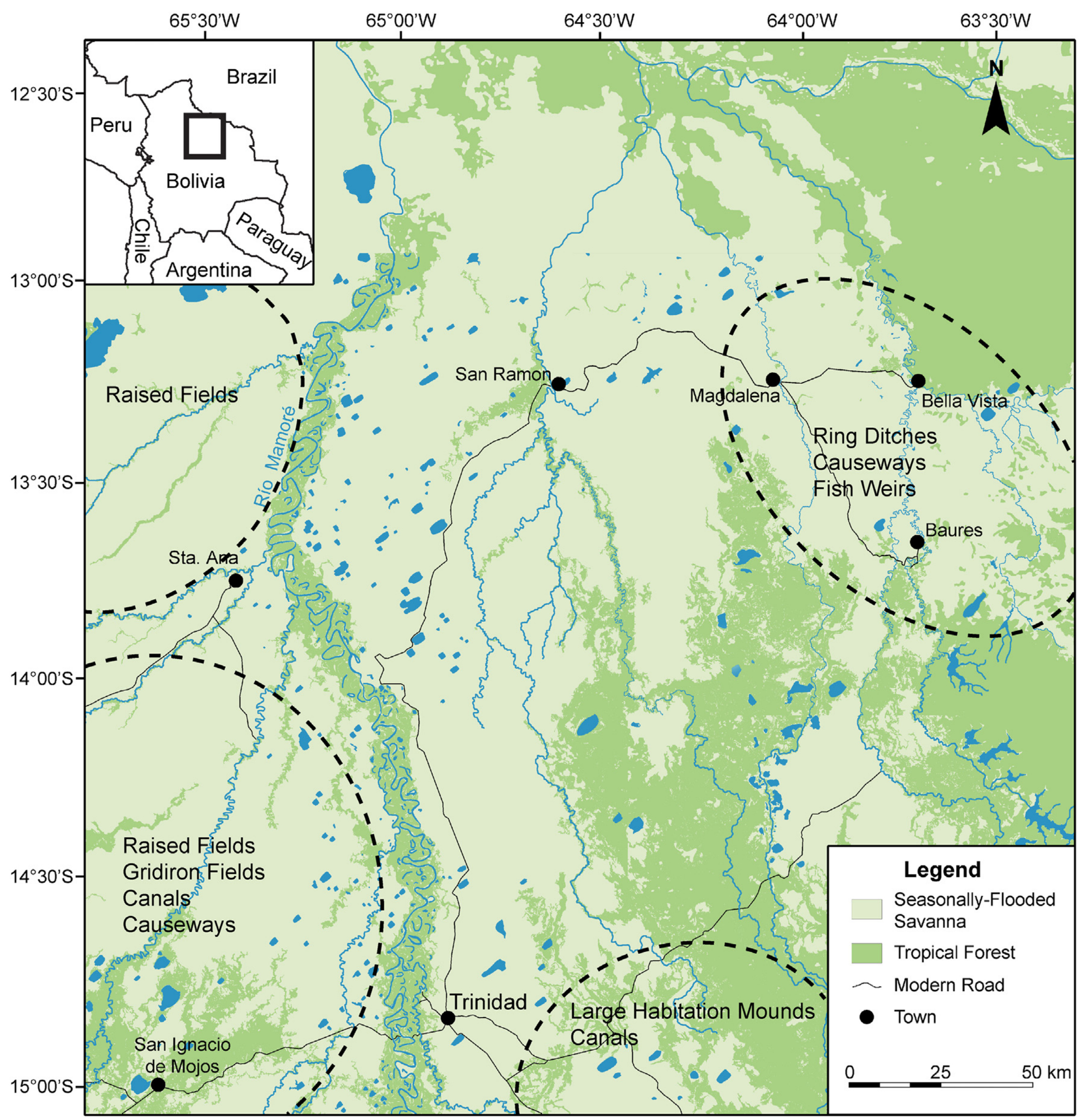

Fig. 3. Map showing the distribution of different types of pre-Columbian earthworks across the seasonally-flooded savannas ('Llanos de Mojos') of the Bolivian Beni basin, southwestern Amazonia.

conserve may itself be a legacy of centuries or millennia of human intervention (e.g., Junqueira et al., 2010; Mayle et al., 2007; Renard et al., 2012b; Willis et al., 2007). If tropical forests are to be understood in terms of their biodiversity, ecosystem functioning and, in particular, whether they are inherently susceptible or resilient to anthropogenic disturbance, then this controversy over the geographic scale and intensity of pre-Columbian impacts upon these forests, and the long-term consequences, needs to be resolved. Only by doing so can conservationists hope to make informed decisions about the scale and type of human land use to be allowed (or even promoted?) within protected areas to best conserve the biodiversity and functioning of Amazonia's ecosystems.

Close integration between palaeoecology and archaeology has the potential to resolve these questions, and is an approach that has successfully been employed elsewhere in the neotropics (e.g., origins of agriculture (Piperno and Pearsall, 1998a), maize domestication (Piperno et al., 2007, 2009; Ranere et al., 2009), and the cause of the Maya collapse (Haug et al., 2003; Hodell et al., 2005)), but, with a few exceptions (e.g., Berrio et al., 2001; Iriarte et al., 2012), has not yet been adopted in lowland Amazonia. This paper therefore aims to address the following two questions:

1. How can palaeoecology, when integrated with archaeology, advance understanding of pre-Columbian cultures and their impacts upon Amazonian ecosystems? In other words, what can palaeoecology contribute to Amazonian archaeology?
2. How can Amazonian palaeoecology and archaeology be closely integrated, and what important research questions can be tackled by doing so?

2. What can palaeoecology contribute to archaeology with respect to pre-Columbian amazonia?

2.1. Chronology

Palaeoecological studies, based on analysis of micro/macroscopic plant remains within lake sediments (e.g., pollen, charcoal, phytoliths), typically comprise continuous, uninterrupted time-series spanning sub-centennial to multi-millennial and sometimes even glacial–interglacial time-scales. If cultural indicators are found within these lake sediments (e.g., evidence of agriculture, arboriculture, deforestation, burning), then the culture identified via artefactual remains at a nearby archaeological site may be placed within a potentially high-resolution temporal framework via its cultural legacy recorded in the neighbouring palaeoenvironmental record of radiocarbon-dated lake sediments. Integration of palaeoecology and archaeology in this way would provide important details about the history of that culture (e.g., when did the culture arise, how long did it thrive, and when did it disappear?).

2.2. Environmental context and human activity

Another key advantage of palaeoecology is that it can offer archaeologists the environmental context for their human occupation sites, and help address questions such as the following. To what extent did these pre-Columbian cultures disturb their tropical ecosystems? Were geometric earthworks (geoglyphs) built within small forest clearings, or was large-scale deforestation carried out to clear the land instead? Was the forest burned so frequently and managed so intensively (e.g., through selection of economically important species) that it was effectively transformed into a 'cultural parkland' (Heckenberger et al., 2003) or 'domesticated landscape' (Balée, 1989; Erickson and Balée, 2006)? Palaeoecological investigations, based upon analyses of pollen, phytoliths, stable carbon isotopes, and charcoal of lake sediments, and/or soils (e.g., Bush et al., 2007a,b; 2008; De Freitas et al., 2001; Iriarte et al., 2010, 2012; McMichael et al., 2012a,b; Pessenda et al., 1998), offer the potential for directly testing these hypotheses with empirical palaeo data.

Past spatio-temporal changes in open herbaceous vegetation, old-growth forest, and early-successional forest, can be reliably distinguished by both pollen and phytolith analyses (e.g., Gosling et al., 2009; McMichael et al., 2012a,b). These palaeo-vegetation proxies also have the potential for identifying more subtle compositional changes in past vegetation communities, especially in light of recent methodological advances. For example, pollen of the important neotropical tree family Moraceae, which dominates most Amazonian forest pollen records, can now, not only be differentiated from Urticaceae pollen, but can also be identified to genus level; e.g., *Brosimum*, *Psuedolmedia*, *Pourouma*, *Maquira*, *Sorocea*, *Maclura*, *Helicostylis* (Burn and Mayle, 2008). Furthermore, improvements to the technique for concentrating large, rare pollen grains from lake/bog sediment samples (Whitney et al., 2012) now means that palynologists' ability to detect pollen of important cultigens, such as maize, manioc, and sweet potato, is greatly enhanced. With respect to phytoliths, on-going refinements in the identification of their micromorphological features and three-dimensional morphology, together with the application of multivariate statistical analyses, are allowing palaeo-ethnobotanists to distinguish phytolith morphotypes to greater taxonomic resolution (e.g., Fredlund and Tieszen, 1994; Piperno and Pearsall, 1998b; Zhao et al., 1998; Mindzie et al., 2001; Pearsall et al., 2003; Piperno and Stothert, 2003).

Charcoal and charred-phytolith analyses provide the basis for reconstructing past changes in fire regime, while the combination of phytolith and carbon isotope analyses from soil profiles also has the potential to distinguish the natural versus anthropogenic genesis of landscapes (Renard et al., 2012a). Non-pollen palynomorphs (e.g., *Sporormiella* fungal spores) may also provide important additional insights into pre- versus post-Columbian ecosystem changes within lake catchments, particularly in the Beni basin of Bolivia. These spores are indicative of mega-herbivore dung (Raper and Bush, 2009). Given that mega-herbivores were largely absent from the lowland Americas until the introduction of horses and cattle by Europeans, and that the timing of first introduction of cattle to the Beni basin by Jesuits is well documented in historical archives (Bacci, 2010), a marked increase in concentration of *Sporormiella* spores in lake sediments of the savannah-dominated Beni basin may potentially provide a chronological marker for the establishment of Jesuit missions and cattle ranching. Evidence of cattle may also have a bearing on the underlying cause of any changes in fire regime and/or tree cover that may have occurred around this time.

Of particular interest to archaeologists is the degree of intervisibility between archaeological sites. For example, were funerary/ceremonial sites, such as the Amapá megaliths or the Acre geoglyphs, built to be viewed from far away, perhaps to broadcast across the landscape the death or burial of an important person? Or were these burials instead carried out in small clearings amidst a more private, intimate forested setting? Alongside the increasing use of digital terrain models and GIS by Neotropical archaeologists (e.g., Östen et al., 2011; Saldanha, 2008), palaeoecologists can play a key role in helping to address such questions by determining the degree of openness of the vegetation at the time of site construction/occupation (e.g., tall, closed-canopy forest versus open grassland/savanna).

2.3. Climate change

Palaeoenvironmental studies can also provide information about past climate change, either indirectly, via climate-driven

vegetation changes, or directly via lake-level (precipitation) changes. An understanding of past climatic changes is crucial because they may have acted as catalysts that triggered a variety of human responses, including population aggregation or dispersion, changes in economic strategies and land-use patterns, restructuring of social organization, as well as, in some instances, cultural collapse (but see papers in Bawden and Reycraft (2000) and McAnany and Yoffee (2010)).

There is a large body of multi-proxy evidence (e.g., diatoms, sedimentology, stable isotopes) from numerous high-Andean tropical lakes for major lake-level (and hence precipitation) changes through the Holocene, the most extensively studied of which is Lake Titicaca (e.g., Abbott et al., 1997; Baker et al., 2001; Gosling et al., 2008). Although this site is perched ontop of the Altiplano at ca. 4000 m elevation, it receives most of its precipitation from the Amazon lowlands via the South American Summer Monsoon, which means that palaeo-precipitation records from this site are also representative of lowland southwestern Amazonia (Baker et al., 2001). This is borne out by lacustrine fossil pollen evidence for climate-driven Holocene vegetation dynamics in lowland Bolivia in tune with Lake Titicaca lake-level fluctuations (Mayle et al., 2000; Whitney et al., 2011). These vegetation responses may be manifested as compositional changes to tropical forests (e.g., changing proportions of rainforest versus dry forest taxa) (Whitney et al., 2011) or even wholesale forest-savanna biome shifts (Mayle et al., 2000; Burbridge et al., 2004).

In the context of the debate concerning the extent to which pre-Columbian Amazonian societies altered their rainforest and savanna environments, it is essential to consider the substantial body of palaeo evidence for major changes in precipitation through the Holocene (reviewed by Mayle and Power, 2008), given the likely consequences for pre-Columbian societies in terms of the sustainability of natural resource exploitation and agricultural productivity. Obvious examples are the late Holocene pre-Columbian cultures of the seasonally-flooded savannas of the Bolivian Beni. Raised-field agriculture (Lombardo et al., 2011a) and fishing, using landscape-scale fish weirs (Erickson, 2000), were clearly dependent upon agricultural and aquaculture systems fine tuned to the seasonal flood regime. One can reasonably hypothesise that increased drought frequency would have had severe consequences for these wetland cultures. The reverse is also true – catastrophic flooding of the Mamoré and Beni rivers, associated with La Niña events, would no doubt have severely impacted these pre-Columbian cultures, as it does subsistence farmers today (Oxfam, 2009).

3. How can palaeoecological and archaeological approaches be effectively coupled?

The publication in high-impact, inter-disciplinary journals of increasing evidence of complex pre-Columbian societies (e.g., Erickson, 2000; Heckenberger et al., 2003; Mann, 2008), which has spurred the ongoing debate over Amazonia as pristine wilderness versus 'cultural parkland', has forced palaeoecologists in recent years to re-evaluate their assumptions of virgin wilderness and design palaeoecological studies to explicitly test for significant anthropogenic ecosystem disturbance in pre-Columbian times (e.g., Bush et al., 2008; McMichael et al., 2012a,b).

3.1. Matching spatial resolution

If the aim is to record small-scale human land use, such as shifting agriculture, in palaeoecological records, then small lakes should be chosen (ideally <100 m diameter), as they would be expected to have a more localised (small-scale) pollen catchment, that better matches the spatial scale of individual forest clearings, than larger lakes (>100 m diameter) with more regional pollen source areas (at least with respect to wind-pollinated taxa such as Poaceae, Cyperaceae, Moraceae, *Celtis*) (Jacobson and Bradshaw, 1981). However, if a clear anthropogenic signal is found in the sedimentary record of a given small lake, such as high charcoal concentrations and maize pollen, then the question arises as to whether this anthropogenic signal is merely a local anomaly, or instead representative of a broader geographic area. An effective approach to resolving this problem is to analyse the sediment cores of tight clusters of small lakes, successfully adopted by Bush et al. (2000, 2007a,b) in different areas of the Amazon basin. These authors demonstrated that, for discrete study areas in both eastern and western Amazonia, palaeoecological evidence for pre-Columbian disturbance was highly localised – maize and charcoal abundant at one site, but sparse/negligible in a neighbouring lake record just a few kilometres away, despite both lakes being small and of comparable size. These findings demonstrate the fine-scale spatial heterogeneity of past human impacts upon Amazonian ecosystems and reveal that, for these areas at least, one cannot assume that human land use identified from the local catchment of a small lake is also representative of a broader, regional geographic scale.

An alternative approach is to pair small lakes with neighbouring large lakes. If the small lake has a local land-use signature (e.g., forest clearance, burning), comparison with the pollen record from the large lake should reveal whether such forest clearance was merely localised (i.e., restricted to the small lake catchment and insignificant at the regional-scale catchment of the large lake) or regional in extent (dominating the catchments of both lakes).

It is important to note though, that these relationships between lake size and geographic pollen source area are, at best, only theoretical conceptual models for neotropical lakes, and have only been developed into quantitative mathematical models, tested against empirical surface pollen and vegetation data, in mid/high latitude temperate/boreal regions (e.g., Bunting and Middleton, 2005; Bradshaw and Webb, 1985; Davis et al., 1991; Prentice, 1985; Sugita, 1993). Furthermore, relationships between lake size and pollen source area may be fairly straightforward and robust in mid-high latitudes where most trees are wind pollinated (Jacobson and Bradshaw, 1981). The much greater variety of pollination strategies (and consequently, range of pollen dispersal distances) among tropical tree species (Bush, 1991), not to mention the far higher *alpha* diversity of tropical forests, means that the relationship between lake size and pollen source area may be less clear in Amazonia than in northwestern Europe or eastern North America.

A novel approach to investigating the geographic scale that a lake's palaeoevegetation history represents has been conducted by McMichael et al. (2012b), who closely integrated lake sediment fossil pollen and charcoal records with phytolith and charcoal records from numerous randomly distributed soil cores within a few hundred metres of the lakes. These carefully designed studies by Bush et al. (2007a,b) and McMichael et al. (2012a) demonstrate promisingly that, with careful site selection and choice of palaeoenvironmental proxy, spatial scales of sufficiently fine-grained resolution can be achieved to detect human land use on the scale of forest clearings and slash-and-burn agriculture.

3.2. Close proximity

Naturally, the most important requirement for effectively integrating palaeoecology with archaeology, is that the lake chosen for palaeoecological study is located close to the archaeological site. For example, if maize phytoliths are found in pre-Columbian raised-field soils, and maize pollen and/or phytoliths are also found in the

sediments of a nearby lake, within a few tens or hundreds of metres, then one can confidently infer that the lake sediment maize pollen/phytoliths originated from the neighbouring raised fields (Iriarte et al., 2012). If so, then the chronology of maize appearance and disappearance in the radiocarbon-dated lake sediment record can be used to infer the timing of construction and abandonment of those raised fields. Obviously, such an inference is more tenuous the further away the lake is from the raised fields.

3.3. Multi-proxy analyses

Only through multi-proxy analyses can palaeoecology be fully integrated with archaeology. Pollen is well preserved in lake sediments and peat bogs, due to the anoxic conditions of those environments, and is the most widely used tool for reconstructing vegetation histories. However, pollen is poorly preserved in most soils, due to aerobic conditions favouring microbial decomposition. Phytoliths, on the other hand, are well preserved, not only in anaerobic lake/bog sediments, but also soils. The *in situ* nature of phytolith deposition also makes them advantageous for the study of past agricultural landscapes; in particular, determining which crops have been locally planted on agricultural features, such as raised fields. For example, maize (*Zea mays* L.) phytoliths have been recovered from several pre-Columbian raised-field complexes in the neotropics (Iriarte and Dickau, 2012; Iriarte et al., 2010; Pearsall, 1987; Siemens et al., 1988). Furthermore, different parts of the plant may contain diagnostic phytoliths, as exemplified by maize, which produces diagnostic phytolith assemblages of cross-shaped bodies in the leaves and wavy- and ruffle-top rondels in the cob (Iriarte, 2003; Pearsall et al., 2003; Piperno, 2006). The recovery of maize leaf and cob phytoliths in raised-field profiles in French Guiana has led Iriarte et al. (2010) to suggest that pre-Columbian farmers practiced green composting, using crop residues after harvest.

Starch-grain research is also now providing robust information on root-crop consumption in tropical regions of the Americas and elsewhere (Denham et al., 2003; Dickau et al., 2007; Duncan et al., 2009; Iriarte et al., 2004; Pearsall et al., 2004; Piperno, 2006; Piperno et al., 2009). Many of these studies involved the analysis of starch-grain residues from stone tools (e.g., grinding stones, chipped stone), ceramic and gourd containers, as well as ceramic graters and corianders used to process plants. Starch-residue analysis has also illuminated the functions of these tools and forced revisions to traditional interpretations of stone tool usage that were based upon less direct forms of evidence, such as ethnographic analogy (Perry, 2004, 2005). For example, the combination of macro- (Bruno, 2010) and micro-botanical (Dickau et al., 2012) analyses from habitation mounds in the 'Llanos de Mojos' is revealing the consumption of a diversity of plant resources, including cereal grains like maize (*Zea mays*), root crops such as manioc (*Manihot esculenta*) and yams (*Dioscorea* sp.), vegetables such as squash (*Cucurbita* sp.) and peanuts (*Arachis hypogaea*), spices (*Capsicum* sp.) and industrial crops such as cotton (*Gossypium* sp.), among others like palms. Analyses of macro- and micro-botanical remains are therefore needed to provide direct evidence of which plant taxa were consumed, cultivated or utilised at the archaeological site in question (whether a raised field, habitation mound, or other earth-mound feature), which can then be cross-correlated with the pollen-based vegetation history determined from sediment cores from neighbouring lakes.

Aside from the issue of differential preservation between pollen and phytoliths, these different vegetation proxies also complement one another in terms of differing taxonomic resolution. Certain key taxa can be identified via their pollen (e.g., *Cecropia*, *Manihot*) but not their phytoliths, and *vice versa* (e.g., Poaceae sub-families, such as Oryzoideae and Bambusoideae; and genera within Cyperaceae and Marantaceae). Utilisation of both of these proxies in tandem therefore provides greater floristic detail than either proxy alone (e.g., Iriarte et al., 2004; Neff et al., 2006; Piperno et al., 1991, 2007; Piperno and Jones, 2003).

Finally, charcoal analysis of lake sediments/soils, considered in the context of pollen/phytolith-based vegetation histories, enables past changes in biomass burning to be reconstructed (e.g., Iriarte et al., 2012; Mayle and Power, 2008). In the absence of charcoal, charred phytoliths may also provide evidence of past burning, as well as which plant taxa were burnt (e.g., Kealhofer and Penny, 1998).

One of the most important reasons for analysing a suite of different palaeoenvironmental proxies, is that it potentially allows one to differentiate between natural, climate-driven, ecosystem changes versus human land use. Although presence of pollen/phytoliths of domesticated crop plants, such as maize for example, is unambiguous evidence of human activity, assigning human agency to changing proportions of 'wild', but potentially economically important, plant taxa (e.g., *Mauritia*, *Sorocea*, *Brosimum*), and disturbance indicators such as *Cecropia* pollen and charcoal, is not straightforward. For example, increased frequency of burning (i.e., charcoal peaks) could equally be due to humans, climate, or interaction of the two. Increased burning is strongly associated with increased human population density (use of fire as a land-management tool), but also results from longer or more severe dry seasons resulting in drier, and therefore more flammable, vegetation and leaf litter (Mayle and Power, 2008). Furthermore, as happens today in Amazonia (Aragão et al., 2007), humans may be the source of ignition, but the likelihood of controlled anthropogenic fires 'escaping' into much larger wildfires increases under drier conditions. Likewise, peaks in *Cecropia* pollen signify disturbance but disturbances may be natural (e.g., flooding, fire, drought-induced mortality) or anthropogenic.

Chronology is crucial to resolving this problem of causality. Synchronous increases in *Cecropia*, charcoal, economically important plants (wild and cultivated) (e.g., *Mauritia*, *Sorocea*, *Brosimum*, maize, manioc, sweet potato), and grasses and herbs, coincident with a decrease in forest cover (most obvious via a reduction in wind-blown Moraceae pollen) would together provide a very strong suite of evidence for onset of enhanced anthropogenic impact, especially if they correlate with the onset of anthropogenic earth-mound (e.g., 'geoglyph') construction. Conversely, the inverse of these trends would signify reduction of human impact and onset of forest recovery. Even stronger evidence for an anthropogenic cause would be achieved if the timing of reduced human impact (decreases in crops, charcoal, and *Cecropia*, and expansion of forest) coincided with accounts from early Spanish chroniclers, such as Cabello Balboa (ca. A.D. 1600–1604, in Jiménez de la Espada, 1965), for dense native populations just prior to their decimation from European diseases. Even if disentangling human versus climatic signals from a particular palaeoecological record proves to be difficult, by cross-correlating palaeoecological records with independent palaeoclimatic data (e.g., lake-level changes), either from the same core, or other sites in the region (e.g., Lake Titicaca on the Altiplano (e.g. Abbott et al., 1997; Baker et al., 2001), one will be able to infer whether particular vegetation changes were climate-driven or not (Mayle and Power, 2008).

4. Case study – pre-Columbian raised fields in French Guiana

The value of this integrative approach is evident from a recent multi-proxy study by Iriarte et al. (2012) (Fig. 4), who combined a palaeoecological study of a wetland peat core (combining pollen, phytolith, and charcoal analyses) with soil phytolith analyses from neighbouring pre-Columbian savanna raised fields

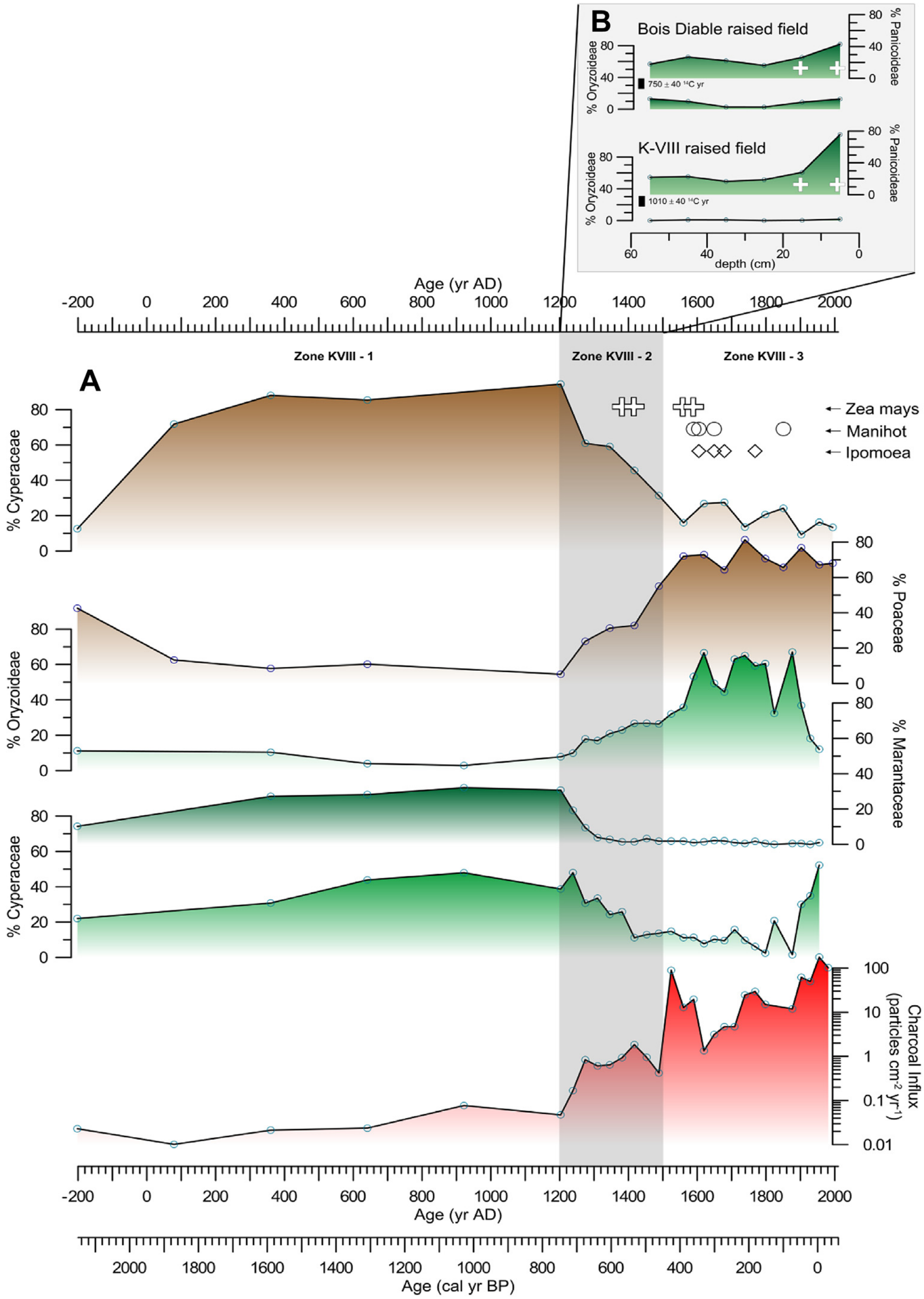

Fig. 4. A: Percentage pollen (brown) and phytolith (green) diagram of selected plant taxa and macroscopic charcoal influx (red) from the K-VIII peat swamp core in coastal French Guiana. Symbols represent presence of cultigens: maize (+), manioc (○), sweet potato (◇). B: Percentage phytolith diagram of selected plant taxa from soil profiles from the K-VIII and Bois Diable pre-Columbian agricultural raised fields. The dates show the age of the uppermost levels of the buried A horizon (peat) immediately below the overlying raised-field soils (modified from Iriarte et al., 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and starch grains from ceramic griddle fragments of habitation sites in French Guiana (Iriarte et al., 2010). Multi-proxy analyses of a peat core from a small 8 ha swamp were integrated with soil phytolith analyses from neighbouring Pre-Columbian raised fields 700 m away. Analyses of charcoal, pollen, and phytoliths from the 31 cm, 2150-yr peat core, at high stratigraphic resolution, provided a continuous, sub-centennial-scale record of changing land use associated with the Columbian Encounter. Radiocarbon dating of the peat core and buried charcoal within the raised-field soils enabled cross-correlation between the datasets from these two sites.

Between ca. 200 B.C. (base of the peat) and A.D. 1200, pollen and phytolith assemblages are dominated by Cyperaceae (wetland sedges), while phytoliths of Marantaceae (another key wetland family, not identifiable by its pollen) are also abundant. Poaceae (grass) percentages (both pollen and phytoliths) are low throughout this period, and macroscopic (>125 μm) charcoal is negligible. This suite of multi-proxy data provides firm evidence

that the local landscape was a seasonally-flooded savanna that rarely burned. At ca. A.D. 1200 marked declines in the wetland taxa Cyperaceae and Marantaceae, coincident with a sharp rise in abundance of Poaceae pollen and the first appearance of maize (*Z. mays*) pollen, demonstrate the initial construction of agricultural raised fields for maize cultivation. Strong corroboratory evidence comes from the presence of maize phytoliths in the soils of nearby raised fields. Given that today, panicoid grasses dominate atop the well-drained raised fields and sedges dominate in the intervening poorly drained canals/ditches, and that similar patterns are evident in the phytolith records of raised-field soil profiles, Iriarte et al. (2012) argue that the declines in Cyperaceae and Marantaceae at A.D. 1200 signify a reduction in the area of seasonally-flooded savanna, whilst the coincident rise in Poaceae pollen most likely reflects expansion of panicoid grasses occupying the newly created *terra firme* (non-flooded) habitat provided by the raised fields.

The close coupling of these peat core and raised-field soil analyses therefore enables much more robust and conclusive inferences to be made about pre-Columbian raised-field agriculture than would be possible from either study alone. Within this multi-proxy, cross-disciplinary framework, the most significant finding from Iriarte et al.'s study comes from the macroscopic charcoal data from the peat core, which overturns previous assumptions about pre-Columbian land use. Instead of a late Holocene trend of increasing charcoal abundance (burning), that mirrors intensification of pre-Columbian land-use, followed by a sharp decline in charcoal (burning) associated with post-A.D. 1492 indigenous population collapse due to European contact (a pattern typical of neotropical forest sites, Dull et al., 2010; Bush et al., 2008), the opposite trend occurs here, whereby charcoal abundance remains low until A.D. 1540, after which it rises sharply at the onset of the colonial period. This charcoal trend implies that, instead of promoting fires for agricultural land management, pre-Columbian raised-field farmers in French Guianan savannas instead actively limited fires. Only after the abandonment of these raised fields and the adoption of a different form of agriculture in colonial times (raised beds in cleared forest) was fire used as an important land-management tool.

5. A strategy for investigating pre-Columbian earth-mound cultures in SW Amazonia

5.1. Pre-Columbian earth-mound cultures of the Bolivian 'Llanos de Mojos'

The above investigation in French Guiana by Iriarte et al. (2012) is a useful exemplar which demonstrates that close integration of palaeoecology (peat swamp core) with archaeology/archaeobotany (raised-field agricultural soils and selected archaeological sediments and plant-processing tools from habitation sites) is able to provide new understanding of pre-Columbian land use in Amazonia. This strategy can be rolled out to other key areas of archaeological interest elsewhere in Amazonia, especially the seasonally-flooded savanna wetlands of the 'Llanos de Mojos' of lowland Bolivia. The latter contains an array of different kinds of Pre-Columbian earthworks (Fig. 3) across a vast area, roughly the size of England (see overview by Lombardo et al. (2011b) and Walker (2008)). In the western half of the Beni (west of the Rio Mamoré) are found vast expanses of raised fields of a variety of sizes, shapes, and orientations, with smaller, narrower raised fields generally concentrated between the towns of Trinidad and San Ignacio, and the larger, wider raised-field platforms concentrated north of Santa Ana de Yacuma (Walker, 2004).

In contrast, to the east of Trinidad, are found numerous, large habitation earth mounds, built upon river levées, that in some cases are up to 30 m in height (e.g., Ibibate mound, Erickson and Balée, 2006). In their 4500 km^2 study area, Lombardo and Prümers (2010) identified as many as 273 earth mounds, ranging in size from <8 ha to >16 ha. Those mounds that have been excavated exhibit a high density of ceramics and contain burials and funerary urns, providing clear evidence that they are artificial (Prümers, 2002), although in some cases they may have originated as abandoned river levées (Lombardo and Prümers, 2010). The eastern part of the Beni is characterised by other types of earthworks – circular ring ditches within forest islands, numerous straight causeways and canals inter-linking these forest islands, as well as zig-zag networks of fish weirs among the open savanna (Erickson, 2000, 2010; Prümers et al., 2006), together spanning an area of $\sim$12,000 km^2 (Erickson, 2010).

This seasonally-flooded landscape is particularly well suited for the closely integrative palaeoecological–archaeological approach espoused in this paper, due to the great abundance of both archaeological (artificial earth-mound) sites and lakes across the region. Fig. 5 shows the close geographic proximity between archaeological sites and lakes (in some cases only tens of metres apart), as well as, in several areas, the ideal mix of paired small and large lakes, allowing local versus regional pollen source areas to be potentially differentiated.

5.2. Pre-Columbian 'geoglyph-building' culture of Acre state, Brazil

Over 300 large geometric earthworks ('geoglyphs'), ranging in size from 100 to 200 m diameter, and with ditches 3–5 m deep, have been discovered across eastern Acre in western Brazilian Amazonia (Figs. 1B and 2), made visible through clearance of the dense overlying rainforest in recent decades (Pärssinen et al., 2009; Schaan et al., 2007, 2008). A key question, of interest to both archaeologists and tropical ecologists, is whether the pre-Columbian societies that constructed these massive earthworks did so with minimal environmental impact (i.e., via small-scale forest clearings, less than a few hundred metres in diameter) or instead by large-scale deforestation across the entire region, which encompasses $\sim$20,000 km^2. A third possibility is that these structures were built within a naturally open ecosystem (savanna) when climatic conditions were too dry to support closed-canopy forest – a plausible scenario given the palynological evidence from NE Bolivia for reduced rainforest cover prior to the last two to three millennia (Mayle et al., 2000; Burbridge et al., 2004).

Palaeoecology has the potential to provide this palaeoenvironmental information. However, unlike the 'Llanos de Mojos' of Bolivia, the lakes in Acre, and indeed most of Amazonia, are almost all riverine ox-bows. Whilst the fossil pollen assemblages of these ox-bows may provide important information about pre-Columbian land use locally among the riparian forests (given their small size, $\sim$0.03 km^2 and therefore predominantly local catchments), it is unlikely that they will be able to record vegetation changes associated with geoglyph construction and abandonment, because most (but not all, see Pärssinen et al., 2009) of these geometric earthworks are at least several kilometres from the rivers, confined to inter-fluvial *terra firme* upland landscapes (Schaan et al., 2008). In such geographic settings, where lakes are not conveniently located close to the archaeological site, an alternative approach involving soil profiles may provide the necessary spatial scale, outlined as follows. A series of soil pits (or soil cores) may be dug along transects radiating out from the geoglyphs, such that pits closest to the geoglyph (e.g., <50 m distant) will capture local-scale forest clearance, while those further along the transect, several kilometres away from the geoglyph, can reveal deforestation at progressively greater spatial scales. Phytolith analyses of soil samples down a 1-m profile, in

Fig. 5. Pre-Columbian earthworks in the Bolivian 'Llanos de Mojos'. A: Ox-bow lake within gallery rainforest, adjacent to pre-Columbian raised fields within seasonally-flooded savanna (west of Rio Mamore, north of Santa Ana de Yacuma). B: Pair of small (L. La Luna) and large (L. Oricore) lakes near Rio San Martin, within the seasonally-flooded savannas of the eastern 'Llanos de Mojos'. C: Ox-bow lake next to pre-Columbian 'ring ditch', outskirts of village of Bella Vista, eastern 'Llanos de Mojos'. D: 'Ring ditch' within *terra firme* forest island, partially encircling Laguna La Luna (B), which lies within seasonally-flooded savanna.

tandem with stable carbon isotope analyses, may provide a temporal record of changes between old-growth rainforest, herbaceous open ground, and early-successional forest re-growth, while charcoal analyses can provide a fire history.

6. Conclusions

Close integration of palaeoecology and archaeology, achieved via careful selection of field sites and use of complementary techniques (e.g., pollen, phytoliths, charcoal, stable carbon isotopes, starch grains, ceramics), can lead to a much more thorough understanding of pre-Columbian cultures, and their land use and environmental impacts, than is possible from either of these disciplines alone. The novel findings that such an approach can yield are amply illustrated by closely integrated analyses of a peat swamp core and soils of neighbouring pre-Columbian raised fields among the seasonally-flooded savannas of French Guiana (Iriarte et al., 2012). Rather than widespread use of fire, as employed by subsistence farmers in savanna regions today, this study shows that the pre-Columbian raised-field agricultural farmers in French Guianan savannas actually limited fires, and that fires only became common-place in colonial times once very different land-use practices had been adopted. These novel insights into pre-Columbian savanna farming may offer important lessons for sustainable land use in seasonally-flooded savannas today – by limiting fires, rather than promoting them, not only would fewer soil nutrients be lost (Dezzeo and Chacón, 2005), but carbon emissions to the atmosphere would also be reduced (Andreae and Merlet, 2001).

The inter-disciplinary approach promoted in this paper also has the potential to resolve the spatial scale of environmental impact (e.g., deforestation) associated with different pre-Columbian cultures. For example, did the geoglyph-builders of Acre state build these geometric earthworks within small-scale forest clearings, hidden from view, or instead build them within a vast, deforested landscape, to be seen from afar? If the latter is found to be true, by multi-proxy analyses of transects of soil pits, then vast swathes of Acre's rainforest, assumed by most tropical ecologists to be pristine old-growth forest (Daly and Silveira, 2008), will instead be shown to be secondary forest re-growth, perhaps no more than 500 years old, post-dating the collapse of this culture following the Columbian Encounter (i.e., post A.D. 1492). Knowledge of the geographic scale of deforestation practised by such pre-Columbian cultures, not only reveals the extent to which they transformed or 'domesticated' their rainforest environment, but will also have important implications for understanding current patterns of biodiversity and the ability of rainforest to recover from disturbance – important considerations for conservation biologists.

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